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EQUIVALENT CIRCUITS FOR RESIDENCE ELECTRICAL SERVICES, INCLUDING GROUND NETWORKS

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For the purpose of determining sources of residential magnetic fields, equivalent circuits for local primary and secondary distribution networks are analyzed. The analysis focuses on 120/240-volt service drops to homes, emphasizing neutral and ground return paths, and illustrates possible interactions between neighbouring homes. Phase differences may occur with induced currents or 3-phase primaries, and must be anticipated in a measuring program. An example is given of adjacent buildings which appear to be exchanging sizable ground currents flowing through a common water service.

INTRODUCTION

As part of a research program to characterize the magnitude of magnetic fields in residences, the Research Division has developed a source characterization study aimed at understanding the current paths inside and in the near vicinity of residential buildings. The accompanying report "Evaluation of Residential Magnetic Field Sources" (E88-17-K), and this report, present respectively a preliminary model for the current sources and their equivalent circuits in a typical residential environment. The equivalent circuits will aid the modelling of magnetic fields resulting from observed currents and the development of coordinated instrumentation for those fields and currents.

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Sources of fields may be roughly categorized as shown in Figure 1, based on the physical location of the currents responsible. The sources are household branch circuit wiring and appliances, distribution and transmission lines, and currents flowing in ground networks. The last category is often suggested as a prime source of fields[1,2], but very little work has been done to estimate its importance quantitatively.

Ground currents have several sources. Unbalanced loads in a residential 120/240-volt service normally result in current flow in the neutral return conductor. In Ontario, wiring codes specify that the neutral must be grounded at the service entrance; the preferred ground is the urban water service. This provides a parallel return path to the grounded center tap of the service transformer. The division ratio of currents depends on the relative impedances of the paths; ground resistances can be very low for copper piping solidly connected to a local main.

Two other sources may contribute to currents in ground conductors. First, ground currents originating in a given residence may flow via common neutral conductors and a common ground network into nearby residences. Second, the loop formed by the separated neutral and ground return may couple to fields generated by distribution and transmission lines and secondary services.

A minor category of household conductors is indicated in Figure 1 for completeness. This includes other possible loops such as household plumbing and hot water heating. These may couple to fields by proximity in one part of the residence and lead to current flows in other locations.

This report presents an analysis of neutral and ground paths in individual residences and nearby primary and secondary supply conductors; two typical distribution configurations are used as examples. The intent is to provide insight into current paths as part of developing a measurement program for these currents. The equivalent circuits can also serve as the basis for numerical modelling and indicate the relevant electrical parameters that are needed.

SINGLE RESIDENCE EQUIVALENT CIRCUIT

A single residential service is illustrated in Figure 2, showing two sides of the 120/240-volt supply. Each feeds a number of branch circuits; the total loads on each side are represented by R1 and R2[3]. The conductor designated a-b represents all return paths to the transformer secondary centre tap. When loads are unbalanced, as is almost always the case with random power usage, the unbalanced or difference current I1 - I2 will flow in this neutral return path.

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1. Electrical Wiring Configurations and Childhood Cancer. N. Wertheimer and E. Leeper. Am. J. Epidemiol 109:273-284, 1979.

2. 60-Hz Residential Magnetic Fields Produced by Ground Currents. S. M. Harvey. Research Report E86-21-K (1986).

3. Residential loads are primarily resistive. If heavy motor loads or extensive fluorescent lighting are present, a reactive component may also exist, and the analysis that follows will need some modification with respect to phases. In industrial and institutional buildings, reactive components must certainly be considered, as well as an extension to 3-phase supplies.

To focus on current in the return paths, we will remove the path a-b and introduce the Norton equivalent seen at these terminals (Figure 3). By moving into the current domain, we adopt the unbalanced current as a given source and consequently are only concerned with impedances in the neutral and ground paths[4].

Figure 4 shows an equivalent representation of a single household, with unbalanced current returning to the transformer secondary centre tap (assumed grounded) via the neutral conductor and also through a ground path. Impedances of the paths have been omitted from the diagram for simplicity. At this point it is immaterial if the current source is identified with the transformer or the house; however when several houses along a street are considered, actual current paths are clarified if a current source is physically identified with each house. This circuit simplification is possible so long as the transformer and secondary bus present a reasonably "stiff" voltage source at each service drop.

The service drop normally enters a house from an outside meter location, passing through a conduit-mast or fed from underground. For safety reasons, wiring codes specify that the neutral conductor at the service entrance must be attached to a metallic water main connection where it enters the building, or in rural situations, to an external ground rod. When currents in the three conductors of a service drop are totally balanced, the magnetic fields generated within the house cancel as a result of very close conductor spacing. However, when current divides between neutral conductor and ground paths, a large current loop is formed and longer range magnetic fields are generated. These may contribute significantly to fields in the house.

Occasionally a situation occurs where a poor connection in the neutral results in all unbalanced current flowing through the ground conductor. This situation may pass unnoticed until the ground path is broken, resulting in voltage irregularities in the home.

In calculating magnetic fields from the currents, it must be remembered that some buses in the equivalent circuits, such as L in Figure 4 and below, are physically composed of several conductors carrying different currents. If the separation or the current is large enough, the dipole field must be considered within the residence or in nearby conductor loops.

EQUIVALENT CIRCUITS FOR A STREET

The extension of these concepts to a number of houses located along a street is shown in Figures 5 and 6. Figure 5 shows a wiring diagram for a typical street with overhead wiring supplied by a single phase primary circuit. In this case a common neutral serves both primary and secondary, and provides a link between houses fed from different transformers. The neutral is generally connected to a ground rod at each transformer, forming an alternate return path from the household service ground.

In Figure 6, the equivalent circuit is shown, including a ground network which may be formed by connections to a common water supply. Each house is represented by its own current source. This drawing accurately represents the paths of line and neutral currents, and uses unbalanced

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4. In nearly all cases of interest, the impedance of the dominant return path will be far lower than that of household loads. If this is not the case, voltage levels in the residence will be irregular.

current as a source variable that is easily measured. Current in both primary and secondary buses must be considered as a direct source of fields in homes and a source of induced current in loops.

It is easily seen from Figure 6, that ground current originating in one house can flow through the ground and neutral connections of other houses, if a very low impedance path is formed by the water distribution network. The impedance of the conduction path through soil will play a role in determining whether ground currents pass through other houses or return directly to the distribution transformer.

Although this equivalent circuit can be analyzed for each source independently, relative phases of currents must be considered in adding magnetic fields.

In Figures 7 and 8, another common distribution configuration is shown. A three-phase four-wire primary is tapped periodically for distribution transformers. The interconnections between houses via ground and neutral conductors is apparent in the equivalent circuit. In this case, currents in ground paths and fields arising from primary or secondary currents may have a different phase from the house in which they are observed. These are denoted on the source elements by A, B and C.

In Figure 8, additional voltage sources have been included to take account of circulating currents induced by magnetic fields. Induced emf's can in principle be calculated from known magnetic fields and the geometric factors for the coupled loops. Branch impedances must be known to deduce induced currents from these emf's. Coupling by magnetic fields introduces a phase shift of 90 degrees in the emf relative to the source current. Electrostatic coupling may also be included but is slightly more complex to introduce into the circuit model. Again, phase shifts occur in the added source terms.

Possible phase differences in circulating currents must be anticipated when developing instrumentation to identify sources; otherwise, simple measurement of rms currents may show inconsistent sums of phasor quantities. Instruments must either measure phase directly, or measure a sufficient number of quantities to deduce phasor relations.

Other distribution configurations can be modelled using the equivalent circuit principles outlined here. Although these circuits provide the basis for understanding observed current paths, it is not possible to predict current division ratios and exact paths without more detailed knowledge of relative impedances. As these are relatively difficult quantities to measure, they will likely be inferred from observations of current.

EXAMPLE: ADJOINING APARTMENT BLOCKS

The following example of interrelated ground currents was observed while this investigator was accompanying an Ontario Hydro electrical inspector, to view examples of ground connections and service entrance configurations.

Two six-unit apartment blocks adjoin each other, but as they have separate addresses, have electrical and water service independent of each other. Currents were observed with a clamp-on ammeter at the service entrance of each building and are reported in Figure 9; the building was in a state of renovation, and currents would be much higher with full occupancy. Relative cur-

rent directions at each junction are deduced from the measured magnitudes, assuming that all currents are in phase. It appears that the two ground currents are equal (within measurement fluctuations and uncertainties) and we hypothesize they are flowing in a direct path through water pipes immediately outside the buildings. It is possible that the zero current in one neutral conductor is the result of an open connection.

As no phase measurements were made, we have assumed the simplest and most likely case, namely, that all observed currents have the same phase. If this assumption is relaxed, other interpretations of this data are possible which do not require a direct ground connection. This example is meant to show the plausibility of such a current path at this site rather than demonstrate it conclusively.

CONCLUSIONS

We have demonstrated that primary and secondary services along a street can be reduced to simple equivalent circuits for the purpose of identifying ground and neutral current paths in residences. Current paths connecting separated residences through common water supplies are readily apparent.

These equivalent circuits will generally serve for calculations of magnetic fields from unbalanced currents; for the balanced current components, the dipole fields of supply buses must be included.

Because of phase differences inherent in 3-phase primary supplies and in induced currents, measuring instruments must be capable of indicating relative phase in order to identify sources.

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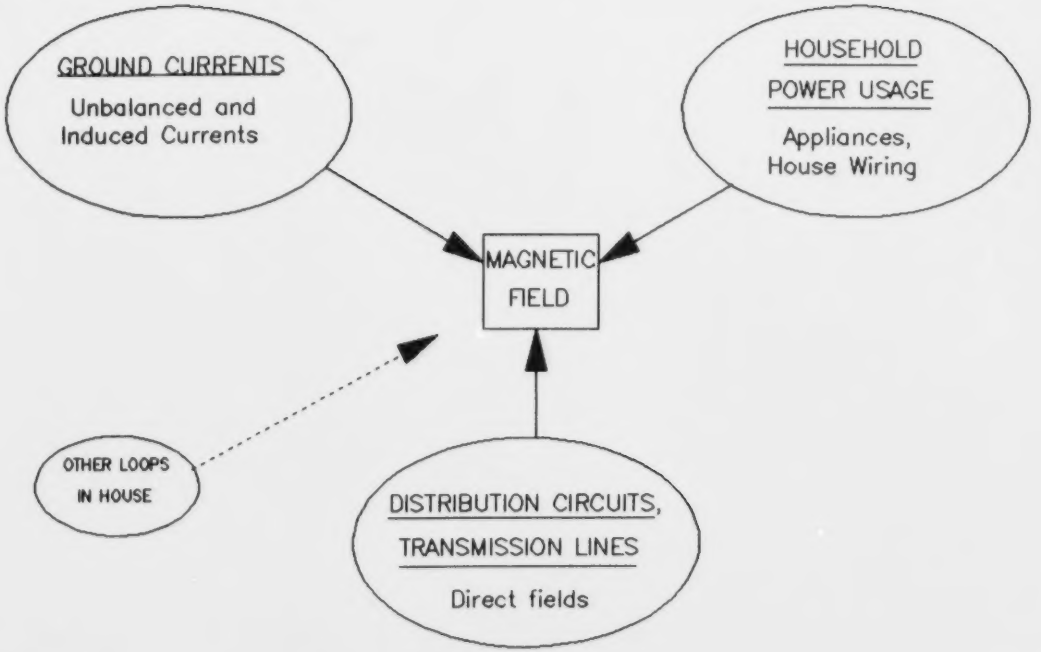

Figure 1: Characterization of Field Sources

Fields are added with regard to direction, phase.

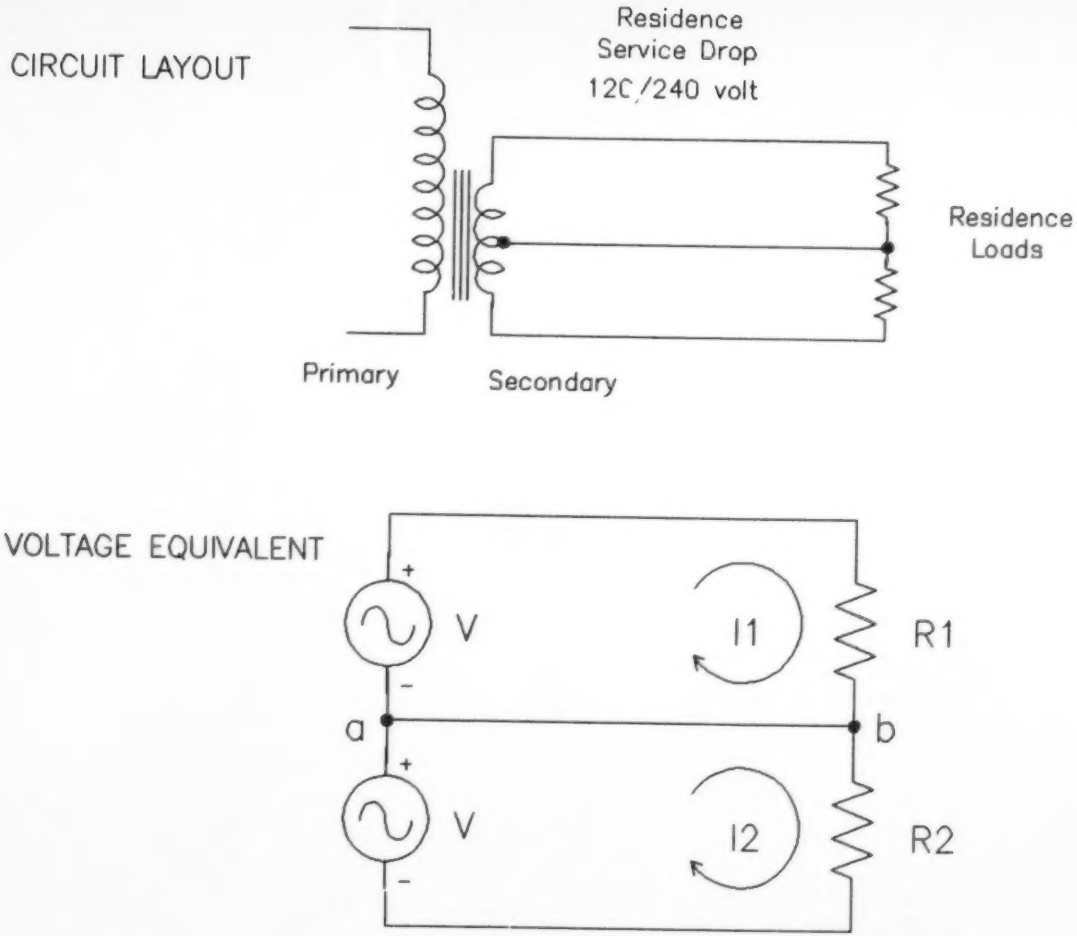

Figure 2: Single Household, Original Circuit

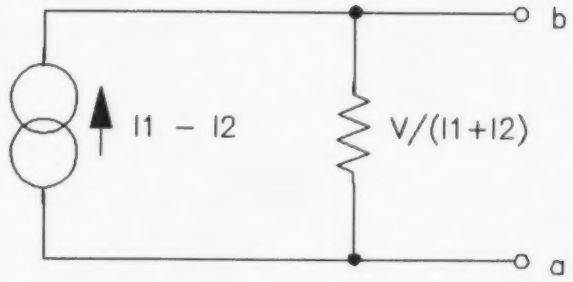

Figure 3: Household Circuit, Norton Equivalent

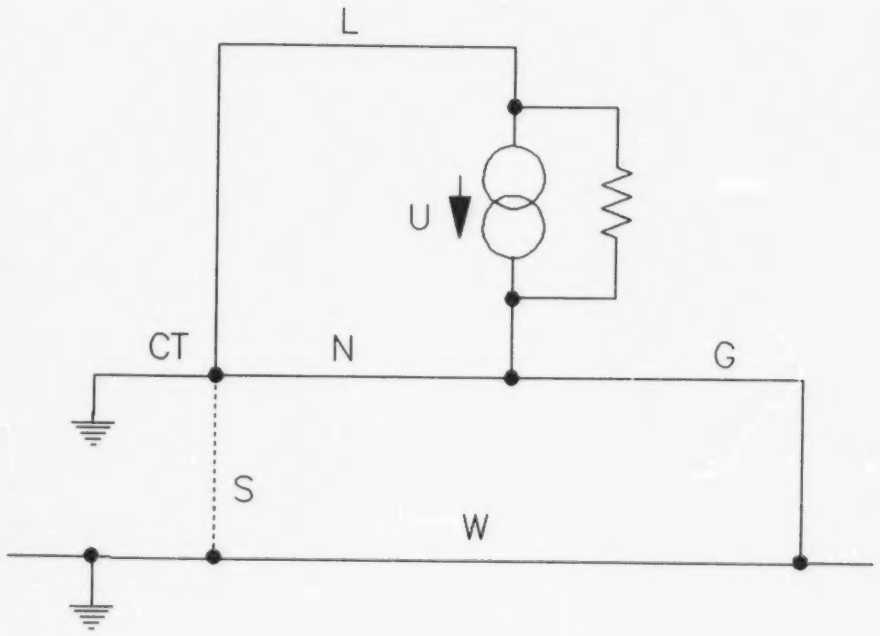

Figure 4:
Single Household with Ground Connection

U – Unbalanced Current
L – Line Supply
N – Neutral Return Conductor
CT – Transformer Centre Tap
G – Ground Conductor
W – Water Service
S – Soil Conduction Path

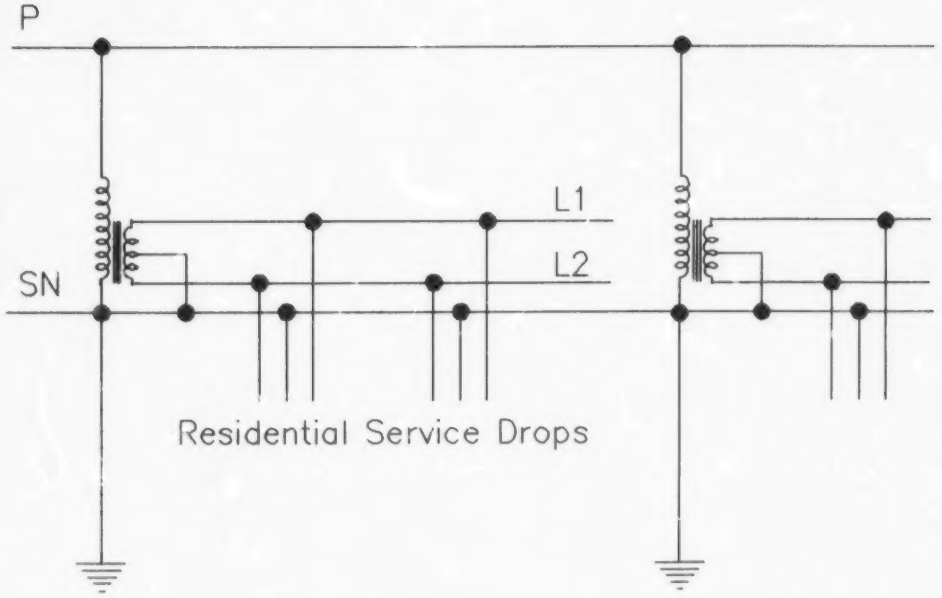

Figure 5: Single Phase Distribution

P – Primary Conductor

SN – System Neutral

L1, L2 – Secondary Conductors

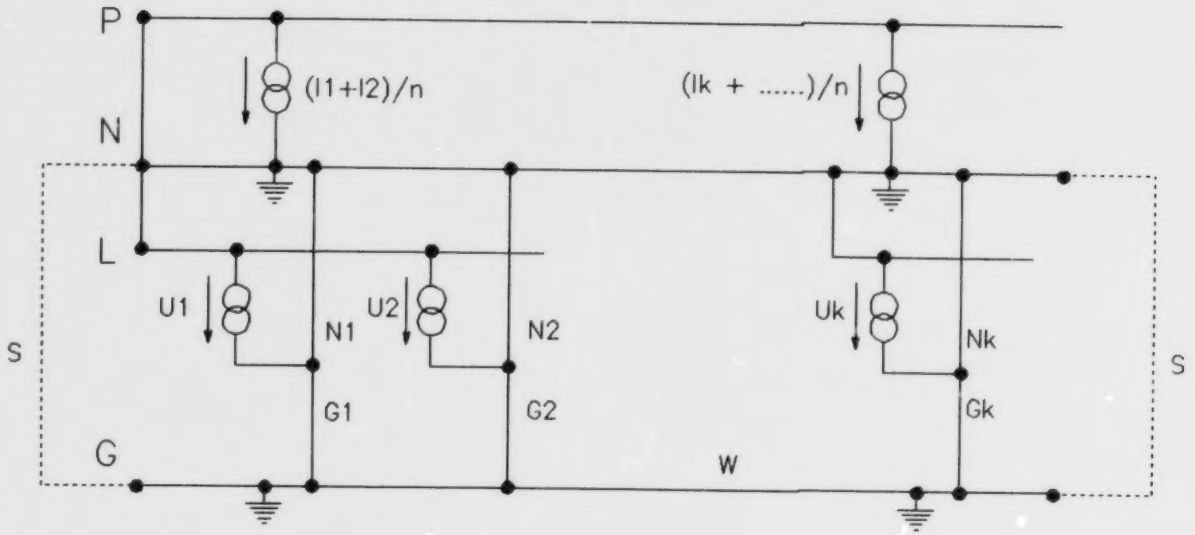

Figure 6: Single Phase Distribution, Equivalent Circuit

L – Secondary Conductors
G – Ground Network
Nk – Neutral Return, House k
Gk – Ground Conductor, House k
Ik – Total Current, House k
n – Transformer Stepdown Ratio
W – Water Pipe and Mains
S – Ground Path through Soil

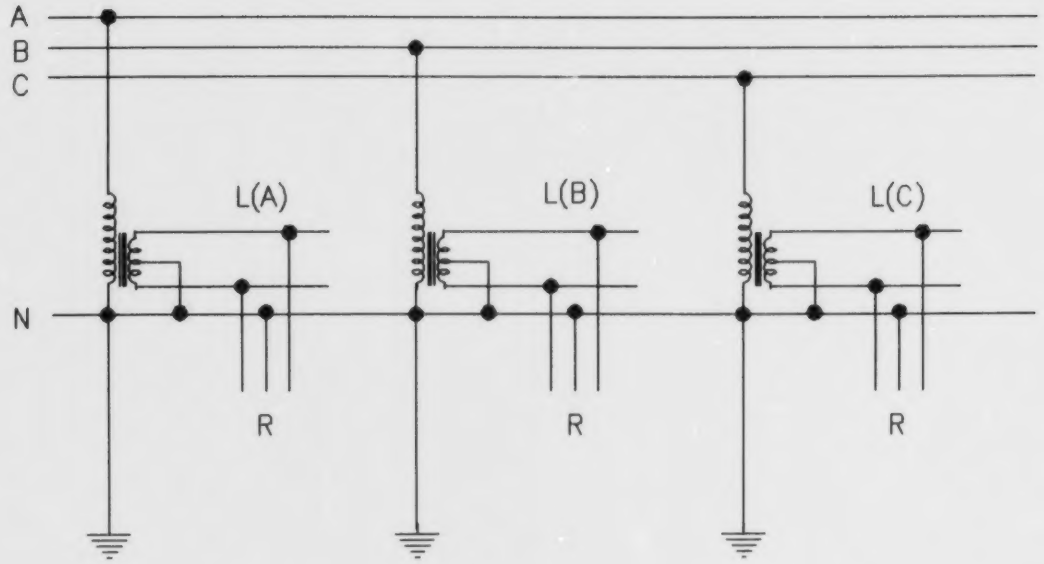

Figure 7: 3–Phase Primary, Common Neutral
A, B, C – Primary Phases
N – Common Neutral
L(A) – Secondary Service, Phase A
R – Residential Service Drops

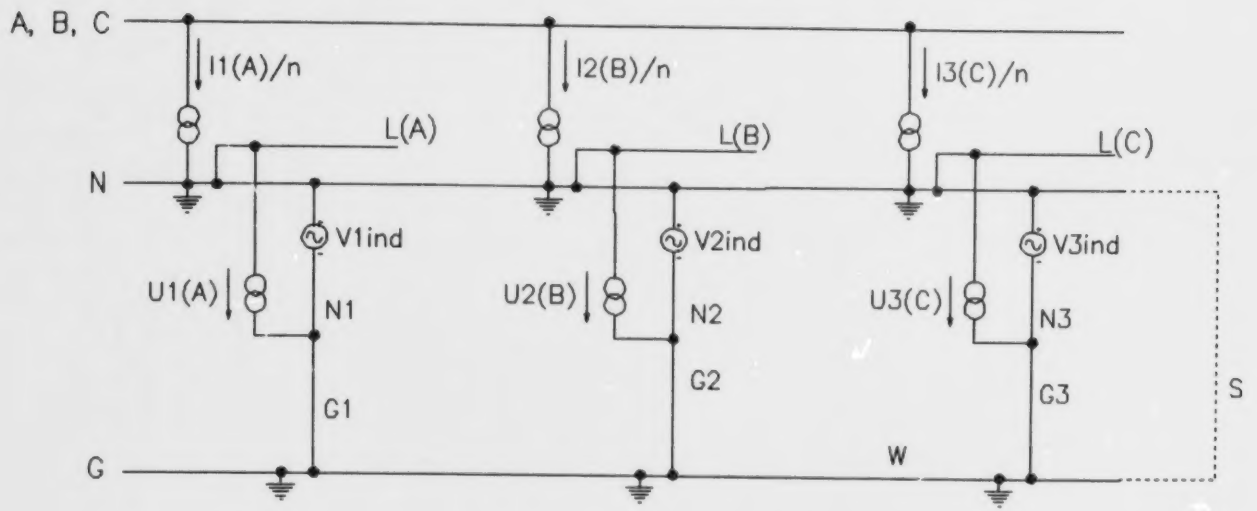

Figure 8: 3–Phase 4–Wire Primary, Equivalent Circuit
A, B, C – Primary Phases
N – Common Neutral Conductor
V1ind – induced emf source
(X) indicates phase of supply voltage
Other symbols as per Figures 6, 7

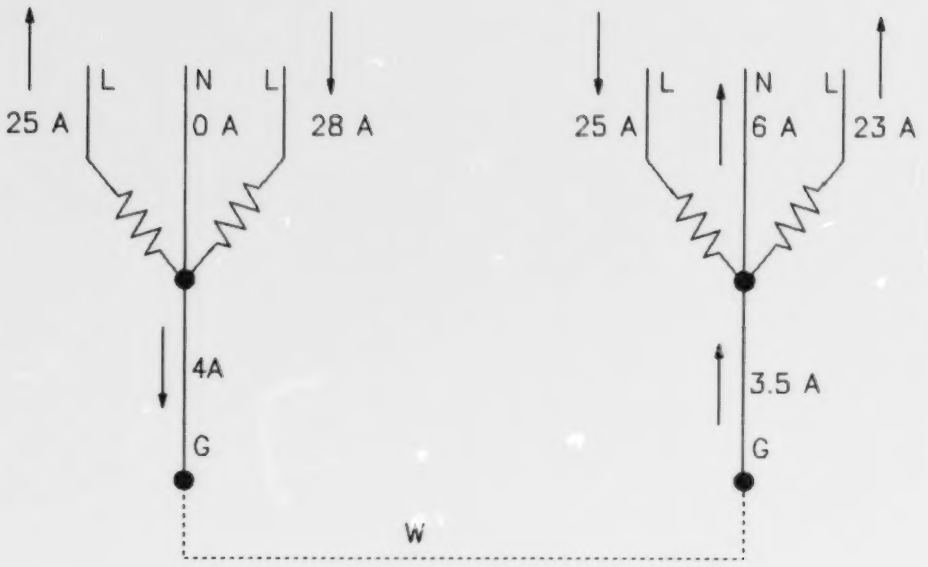

Figure 9: Adjoining Apartment Blocks, Service Entrance Currents

L – 120/240 Volt Lines

N – Neutral Return Conductor

G – Ground Conductor

W – Water Service Ground Path (Suspected)

↑ – Hypothesized Current Direction (Single Phase)